CHARACTERIZING GROUND-WATER FLOW PATHS IN HIGH -ALTITUDE FRACTURED ROCK SETTINGS IMPACTED BY MINING ACTIVITIES

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ABSTRACT

The Rocky Mountains of the western USA have tens of thousands of abandoned, inactive and active sites related to precious- metal (gold, silver, copper) mining. Mining activities often resulted in mobilization and transport of associated heavy metals (zinc, cadmium, lead) which can pose a significant threat to aquatic communities in mountain streams. Transport of heavy metals from sources associated with mining (waste rock piles, tailings impoundments, underground workings, mine pits) can occur along numerous hydrological pathways. Using geological, hydrological and chemical data, pathways can be inferred to aid in developing hypotheses related to transport of metals. These hypotheses can then be tested by conducting ground-water and surface water tracing studies using natural and artificial tracers.

Fractured- rock ground-water systems behave like triple porosity aquifers with, at mine sites, added porosity elements such as adits, stopes and shafts. Ground-water tracing techniques make fewer assumptions about pathways than do hypothetical (e.g. Darcy) or numerical simulations and are therefore more reliable. Fluorescent dyes constitute some of the most analytically sensitive, versatile, non-toxic and inexpensive artificial water tracers available. Surface water tracing allows for very accurate stream flow measurements and the identification of ground-water inflow zones to streams. Tritium activity can be used to help characterize residence time along ground-water flow paths provided there is minimal matrix diffusion. Stable isotopes are useful for characterizing ground-water recharge conditions and for separating surface and subsurface pathways.

These tools used in combination can provide multiple lines of evidence regarding the location and nature of the hydrological flowpaths that transport total and dissolved metals from mining-related sources to mountain streams. An understanding of the nature of the hydrological pathways is very important for appropriate geochemical modeling of metals transport. This paper presents an example of the use of these techniques at an abandoned precious metals mine in Southern Colorado. The results of these types of studies are very useful for helping decide on appropriate remedial actions.

INTRODUCTION

Within the Rocky Mountains of the western USA tens of thousands of abandoned and inactive metal mines are located in environmentally sensitive watersheds. Mining activities often resulted in release and transport of toxic metals (copper, zinc, cadmium and lead) in concentrations which can pose a significant threat to aquatic communities in mountain streams. Transport of heavy metals from sources associated with mining (mine pits, underground workings, tailings impoundments and waste rock piles) to mountain streams occurs along complex ground-water pathways. Using geological, hydrological and chemical data, hypotheses have been developed regarding transport of metals in mountain ground-water systems. Chemical data from water and rock analyses, data from surface-water and ground-water tracing studies, and data from environmental isotope analyses have been particularly useful in testing these hypotheses and delineating ground-water flow paths that are important with regard to loading of toxic metals to mountain streams.

Hydrogeological settings within the intrusive rocks that comprise the Rocky Mountains are typically characterized by steep slopes on the sides of mountains, thin soil cover and highly fractured bedrock (Aller, 1987). The upper 3 to 15 metres of bedrock is commonly highly weathered and, when saturated, comprises a significant water-bearing unit. Below this highly weathered zone ground-water flow occurs predominantly in individual fractures, fracture zones, fault zones, and densely jointed zones. The rock matrix plays a minor role in ground-water flow and typically has low porosity and permeability. Measurement shows that fresh granite has a porosity of about 1%, whereas a weathered specimen of the same rock type has a porosity of about 4% (Cambrian Ground Water, unpublished data). As a result ground-water flow in these settings is highly preferential and controlled primarily by the orientation and distribution of permeable structural features. Due to the mountainous topography steep hydraulic gradients are common within the permeable zones of the rock. In mountain watersheds the topographic drainage basins are not always coincident with ground-water divides. Seasonal ground water level variations commonly range from 15 to 30 metres. As a result the location of ground-water divides can shift seasonally because more and different flow paths are available to ground water when water levels are high than when water levels are low. In the vicinity of hard rock mine sites the subsurface hydrology is further complicated by the presence of underground workings (adits, stopes, shafts, etc.) which perturb the local and intermediate ground-water flow systems.

Because these settings are primarily fracture flow systems the porous medium approach to the study of these rocks often has significant limitations for assessing the hydraulic connection between major permeable structures or zones (ASTM, 1995). Relying only on monitoring wells and the assumptions associated with their use often leads to an inadequate description of the flux of ground-water and contaminants. Ground-water tracing is a useful tool in these hydrogeological settings because tracing techniques make fewer assumptions. The use of fluorescent dyes as tracers is especially helpful because these dyes are analytically sensitive, versatile, non-toxic and can be economically used to study rapid flow paths. Most fluorescent dyes will work well in waters where pH is near neutral. In acidic conditions the fluorescence of some dyes is minimized. However these dyes will usually fluoresce again if the sample is adjusted to more alkaline conditions (Käss,1998).

Tracing techniques can help delineate ground-water flow paths and ground-water flow velocities along the delineated flow paths. Dye recovery data, when combined with ground-water flow data, can also provide quantitative data that can be useful for assessing contaminant behavior and fate in the subsurface. Tracers such as dissolved salts (chloride and bromide) are also commonly used in ground-water studies but do not have the sensitivity of fluorescent dyes. Several tracers can be used together allowing several potential pathways to be evaluated simultaneously. The application of surface water tracing techniques in combination with ground-water tracing provides detailed information on ground-water inflow zones to streams. Stream tracing techniques which include the continuous injection of a constant concentration of a tracer also provide very accurate stream discharge measurements based on dilution of the tracer. Many fluorescent dyes and salt tracers have been approved for use in aquifers and streams which are used to obtain drinking water supplies

Environmental isotopes (including stable and radioactive isotopes) can also be very useful for helping to characterize ground water recharge and flux in fractured rock hydrogeological settings. Isotopes of environmentally important elements (hydrogen, carbon, nitrogen, oxygen, sulfur) occur in precipitation, rocks, surface water and ground water. For a given element isotopic composition can vary due to partitioning or fractionation related to differences in reaction rates. Fractionation is proportional to differences in isotopic mass. This allows the ratios of isotopes to become fingerprints of climatic and hydrogeological conditions. Ratios for selected isotopes of hydrogen, oxygen, sulfur and hydrogen can be useful for segregating sources of inflows to a mine or to a stream. In high altitude settings, variations in annual rainfall and snow melt strongly affects the isotopic composition of melt waters. Isotopic fractionation can be more pronounced in low temperature settings than in warmer settings.

Tritium, a radioactive isotope of hydrogen (half-life = 12.43 yrs), was released to the atmosphere during the period of thermonuclear bomb testing which was at a maximum during the 1950s.The presence of tritium in ground water is an indication that recharge occurred during or after the bomb testing period. In addition to radioactive decay tritium in ground water is subject to significant attenuation by diffusion and dilution by mixing with younger water with less tritium. Because of this tritium concentrations cannot be used to obtain a representative "absolute" age of ground water.

The tools discussed above, used in combination, can provide multiple lines of evidence regarding the location and nature of the ground-water flow paths that transport heavy metals from mining related sources to mountain streams. This paper presents the results of studies using these tools in the Chalk Creek mining district in southern Colorado, USA.

CHALK CREEK MINING DISTRICT

Geology of Ore Body

The Chalk Creek mining district, located within the Chalk Creek watershed, is approximately 160 kilometres from Denver, CO. Chalk Creek and its 14 tributaries drain 24,900 hectares of the eastern slopes of the Collegiate Range west of Buena Vista, CO (Figure 1). Ten lakes occur within the watershed. Chalk Creek flows into the Arkansas River about 16 kilometres south of Buena Vista. The topography is typical of glaciated mountainous regions. Important topographic features in the vicinity of the mining district include serrated rides and U-shaped valleys with steep sides.

The mining district, which lies between 3050 and 3900 metres above mean sea level, is located on the southwestern flanks of the Mount Princeton Batholith, a Tertiary age intrusive body comprised primarily of quartz monzonite. The batholith, nearly 32 kilometres in diameter, is one of the largest intrusive bodies in Colorado. The monzonite is typically gray and medium grained with texture ranging from even-granular to a predominantly porphyritic facies in the central part of the mining district (Figure 2). Gold, silver and lead-zinc deposits are associated with pyritic-quartz veins within the monzonite. Free gold occurred in some of the ore. Within the Chalk Creek district the most significant mineralization occurred in a belt 0.8 to 3.2 kilometres wide and 16 kilometres long that extends from the Continental Divide northeast across Chrysolite Mountain (Dings and Robinson, 1957). Numerous N-NE trending, steeply dipping veins occur within Chrysolite Mountain and the ridges which trend to the south and northeast. The veins range from stringers less than 2.5 cm. thick and less than 15 metres long to lodes 15 metres thick and more than 1.5 kilometres long. Strongly oxidized ore and vein material are confined mostly to the west slope of Chrysolite Mt. Complete or nearly complete oxidation occurs to a depth of about 120 metres and partial oxidation occurs to a depth of about 275 metres. Vein gangue is primarily white vuggy quartz with some calcite, rhodonite, rhodochrosite, barite and fluorite occurring locally.

Mining History

About 75% of the total production of metals (gold, silver, copper, lead and zinc) came from the Mary Murphy group of mines. The Mary Murphy was one of the first mines to be developed within the Chalk Creek district. Raymond (1887) reports that the mine was operating in 1875. The Mary Murphy operated continuously from 1875 to 1925 and intermittently from 1925 to 1951. The period of greatest mining activity occurred from 1883 to 1893 when approximately 10,000 people lived in the mining town of St. Elmo which is now essentially an abandoned "ghost" town.

Five main veins and several smaller ones were worked within the mine. The most important, the Mary Vein, strikes N to N 35° E with an average strike of N 20° E. It dips 75 to 90° W from the surface to 275 metres and 75 to 90° east below 275 metres. The Mary vein outcrops on the surface of Chrysolite Mt. And can be traced for about 1850 metres. This vein was mined to a depth of 430 metres. The mine was worked on 14 main levels and several intermediate levels. Adit portals allowed access to the surface at the 100, 200, 300, 400, 700, 1100 (Lady Murphy adit) 1400 and 2200 (Golf adit) levels (levels are designated by the distance from the top of Chrysolite Mountain in feet). The adit portals for the 700 and 1400 levels opened into Pomeroy Gulch, a tributary to Chalk Creek. Mining did not occur below the 430 metre level.

The adit portal at the 1400 level discharges water continuously with flow ranging from about one to five litres per second. The Golf adit was constructed only as a drainage and haul adit. A 246 metre raise room connected the Golf adit with the 1400 level. Above the 1400 level Chrysolite Mountain is extensively mined out with a complex network of stopes, drifts and crosscuts. Large areas of workings are now caved and partially filled. Ore from the Mary Murphy was originally transported via tram to the Romley Mill (construction date unknown but prior to 1912) located at the mouth of Pomeroy Gulch 1.6 kilometres west of the mine (Figure 3). In 1912 the Mary Murphy mill was constructed and ore was transported via a tram from the upper workings on Chrysolite Mt. After the Golf adit was driven the ore was transported to the Mary Murphy mill via narrow gauge rail. The Tailings generated from the milling process were impounded behind wooden cribbing near the mill on the floodplain sediments of Chalk Creek. More than 53,000 cubic metres of tailings were generated by the mill. The Golf adit continuously discharges water with flow ranging from about 2 litres per second to 8 litres per second.

ENVIRONMENTAL CHARACTERIZATION

In the spring of 1985 the Colorado Division of Wildlife (CDW) reported about 80% mortality of trout fingerlings within 48 hours of introduction to the Chalk Cliffs Fish Rearing Unit trout hatchery located on Chalk Creek 24 kilometres downstream of the Mary Murphy mine (URS Operating Services, 2000). Subsequent sampling of Chalk Creek showed values that in excess of aquatic water quality standards for zinc and cadmium. Subsequent, limited sampling of Chalk Creek from 1986 through 1989 confirmed that dissolved metals in Chalk Creek increased significantly in the reach adjacent to the mining district at Chrysolite Mountain. As a result of this finding, significant attention has been focused on environmental characterization and remediation of the Mary Murphy and Iron Chest mines. Using Clean Water Act monies the Colorado Department of Public Health and the Environment (CDPHE), the Colorado Division of Minerals and Geology (CDMG) and the US Environmental Protection Agency (USEPA) have collaborated on numerous environmental characterization studies and selected, focused remedial activities. Numerous other state, federal and private organizations including the CDW, the US Bureau of Mines (USBOM), the US Bureau of Reclamation (USBOR), the US Geological Survey (USGS), and the Colorado School of Mines (CSM) have provided support and technical expertise. The site has developed into a field research and technology demonstration site for studies on characterization methods, remediation and restoration of hard rock mine sites.

Initial Characterization Efforts

In 1990 an extensive surface-water / ground-water monitoring network was established which included up to 23 surface water locations, ten seeps, 12 ground water wells and three discharges from adit portals. Most of these locations were sampled twice a year from 1990 through 1994. Data from these sampling events were used to help develop conceptual understandings of the hydrogeological setting. During this time zinc concentrations in Chalk Creek below the Chrysolite Mountain mines ranged from 14.3 to 838 µg/l. Dissolved zinc concentrations from wells developed in the alluvial deposits along Chalk Creek ranged from 200 to more than 10,000 µg/l. Three of the five monitoring wells developed in the quartz monzonite had zinc concentrations less than 50 µg/l. Monitoring wells MM-3 and MM-9, located between the Golf adit portal and Chalk Creek and developed in a significant fracture zone in the monzonite, ranged from 10,000 µg/l to 158,000 µg/l. Zinc concentrations in the Golf adit portal discharge typically exceeded 10,000 µg/l and occasionally exceeded 50,000 µg/l.

Using data from the September 1990 and June 1991 sampling events a detailed mass loading was completed for zinc, iron and manganese at the Golf adit and Mary Murphy waste rock/tailings areas (Medine, 1990). Results from this analyses indicated that about 22% of the flow in the reach of Chalk Creek that flows past the Chrysolite Mountain mines is from ground-water discharge. A significant percentage of the total metals loading to Chalk Creek could not be accounted for in the obvious surface discharges associated with the Chrysolite mines. Based on the loading analysis, the concentrations of heavy metals in the ground- water wells, and the nature of the hydrogeological setting it was concluded that more than 20 % of the heavy metals loadings to Chalk Creek occurs via ground-water pathways.

Between July and September 1991 five separate tailings and waste rock piles (approximately 57,000 cubic yards) were consolidated into one pile located immediately downstream of the Golf adit portal. The new pile was covered with two feet of waste rock and two tons per acre of horse manure. Approximately 900 Lodgepole pine and Engleman spruce seedlings were planted on top of the pile. The Golf adit was also unplugged during the summer of 1991. This resulted in a temporary decline in dissolved zinc concentrations in the portal discharge due to precipitation of metals when the adit water was exposed to oxygen. Dissolved zinc concentrations dropped to about 5000 µg/l for a period of a few months. These remedial actions did not result in a significant reduction of zinc and cadmium loading into Chalk Creek. Dissolved zinc concentrations in Chalk Creek from samples taken above and below the mining area in June 1999 were 43 µg/l and 114 µg/l respectively. The dissolved zinc concentrations in the Golf adit portal continue to exceed 10,000 µg/l.

Based on these initial characterization efforts it was decided that additional site investigations should focus on delineating ground- water flow paths and understanding the flow and chemistry of ground-water entering and flowing through the mine workings inside Chrysolite Mountain.

Stream Tracing

Flow in mountain streams can be accurately measured by adding a dye or salt tracer to a stream, measuring the dilution of the tracer as it moves downstream and calculating flow from the amount of dilution of the tracer (Kimball, 1997).If a tracer is injected at a constant rate for a known period of time the total tracer mass added to the stream can be calculated. Stream flow downstream of the injection point can then be calculated if the concentration of the tracer is measured upstream and downstream of the injection point. Mathematically this is expressed as:

$Q_s = (C_i Q_i) / (C_a - C_b)$

where

Q_s is the stream flow or discharge

C_i is the tracer concentration of the injection solution

Q_i is the rate of injection into the stream

C_b is the tracer concentration downstream of the injection point, and

C_a is the tracer concentration upstream of the injection point

This tracer dilution method can also provide data that help determine stream flow velocity, travel time in the stream, the quantity of inflows from tributaries and ground-water discharge and transient storage in stream bed sediments (hyphoreic zone).

In October 1995 the United States Geological Survey conducted a stream tracer study along that stretch of Chalk Creek that passes by the Mary Murphy mines. A sodium chloride tracer was added at a constant rate for 24 hours at a point upstream from the Mary Murphy mine discharges. Chloride concentration was monitored at several points downstream from the injection point. As seen on Figures 5 and 6 in Kimball (1997) there are three main segments on a plot of time versus chloride concentrations at two sites on Chalk Creek. The first shows the arrival at two locations along Chalk Creek. The difference between the arrival times represents the time of travel between the two sites. The difference in chloride concentrations between the two sites along a flatter (plateau) segment is an indication of the difference in discharge at the two sites. The tracer is diluted by water entering Chalk Creek between the two locations. The decrease in chloride concentration resulting from stopping the tracer injection is shown as a third segment and also indicates the travel time between the two locations.

Site to site differences in chloride concentration along the plateau segment are a result of dilution. These differences are used to calculate stream discharge. Numerous synoptic samples were collected along Chalk Creek during the plateau period and analyzed for zinc. Sampling locations for zinc included all surface discharges to Chalk Creek associated with the Golf adit discharge, suspected ground-water inflow zones and surface discharges from an old tailings area downstream of the Golf adit portal. The zinc concentration data and the Chalk Creek discharge data were used to develop a mass loading profile of zinc in the stream. From the synoptic zinc concentrations and the mass loading profile it can be shown that about 6% of the zinc load in the reach of Chalk Creek included in this study comes form upstream sources. The surface inflows associated with discharge from the Golf adit enter Chalk Creek along a reach from 80 to 300 metres below the injection point. These discharges account for about 72% of the total zinc load in Chalk Creek. About 8% of the total zinc load in Chalk Creek is from ground-water discharge via a northeast trending fracture zone in the quartz monzonite. This fracture zone had been partially delineated by previous work at the site. The remaining 14% of the zinc load in this reach of Chalk Creek is from discharge from an area on the floodplain of Chalk underlain by old tailings. This area occurs along the reach from 350 to 615 metres below the injection point.

Ground-Water Tracing

Although at Chalk Creek much information had been gained from other chemical and hydrological data as to the nature of impact to surface water that the mine waste presented, the precise entry points of impacted waters into Chalk Creek, the velocity of the ground

water and the source of the metals (workings, tailings, etc.) was uncertain. Although the ground water in the drain adit (Golf adit, N38ş 40' 49" W108ş 21' 28", 3,154 metres amsl), was known to be impacted, other inputs of water were known to enter the adit that were relatively clean. It was important to describe the possible sources of all these waters, and gain more information about the relative origins of the waters discharging from the Golf adit. Around the mountains there are several draining adits as well as the Golf adit (0.004 m^3/sec.). Some of these are at elevations higher than the Golf adit. A relatively large discharge (0.003 m^3/sec.) was also emerging from the 1400 level adit which is 244 metres above the Golf adit. The 1400 level portal is located on the southwest flank of Chrysolite Mt. above Pomeroy Gulch. This was the largest discharge other than the Golf adit and it was important to determine where the majority of this water was originating as it was impacted by metals. It was decided to use fluorescent dyes to trace these presumed to be relatively rapid-moving waters.

In November 1995 a pilot study was conducted where rhodamine WT (CI Acid Red 388) was injected into inclined holes in the wall of the Golf adit. Ground-water levels in the quartz monzonite were near the annual low. The dye appeared to migrate relatively quickly to a well down gradient from the adit portal. Based on those results a larger-scale test was designed for the following spring when ground-water levels would be near the seasonal high. In addition samples of representative water were collected in the Golf adit for measurement of their $^{234}U/^{238}U$ activity ratios. A relatively recent release of ^{234}U into solution from mining would cause it to be in disequilibrium with its parent and might indicate younger water. In older water ^{234}U would be in greater isotopic equilibrium with its parent. The results were informative in that all the waters were in some mode of disequilibrium - but the differences were not clear enough to be useful. These data did however show that the water in the raise room was in greater disequilibrium to the water in the water-bearing fracture in the Golf Tunnel, which should be expected for a more rapid flow path. This supported a hypothesis that some of the water in the raise room was a younger component. It would be likely that water there might contain a rapid component that was flowing through the mine workings rather than through the fracture network in the bedrock which would be a slower pathway. The uranium series data for water from the fracture and water at the dam in the tunnel were similar to each other but dissimilar to the raise room stream suggesting quite complicated mixing was occurring in the main adit flow.

The large-scale tracer testing using fluorescent dyes was done in the summer of 1996. It was decided that it would be useful to drill a hole into the uppermost workings of the former mine site near some known stopes and in a location that would be at a high-enough altitude so that it would be possible for the 1400 level adit discharge to be a likely tracer recovery location. A 49-metre slanted cored hole was drilled at an elevation of 3,730 metres and thereafter 1.5 kg of the fluorescent dye eosine OJ (CI Acid Red 87) was mixed into a slurry and pumped into the hole. During drilling circulation was lost completely at a depth of about 20 metres so there was adequate permeability through which the tracer might migrate, and it would likely enter the workings as the hole was drilled into stoped areas. At the same time, another tracer test was done accidentally along the road to and from the drill hole location when marmots had eaten through the radiator hoses of a vehicle and the dye-laden antifreeze solution (containing uranine CI Acid Yellow 73) was lost along the road.

The uranine dye from the cooling system of the vehicle was seen the next day in monitoring wells immediately down gradient of the road showing how rapid the recharge is to these wells. The dye was also seen briefly in the adit discharge but not in individual flows into the Golf adit.

Significantly it was not recovered in the discharge from the 1400 level adit portal even though the road goes above and near there and is on the same side of the mountain where the spill occurred. The results from this accidental but useful trace indicated how complicated but efficient the flow systems could be in a mined area even though the geometry of the workings might be reasonably well known.

The eosin OJ injected into the cored hole was recovered several weeks after injection in a well located near Chalk Creek and down the path of the steepest gradient from the cored hole. There appeared to be very little influence from structure on the initial pathway. Further sampling revealed a wetland type area near the point of confluence of Pomeroy Gulch and Chalk Creek may have been the point of discharge of this dye, other flowing adits found nearby (along the same general pathway were also to discharging low concentrations of the dye. Only a small amount of the eosine dye that injected was estimated to have been recovered. This dye recovery showed that there was a rapid flow zone in the bedrock, probably through permeable fractures, possibly through but also possibly below the upper bedrock weathered zone. The dye was not recovered in the mine workings. Eventually this dye was recovered in the wells MM-3, MM-9 and MM-6 below the Golf adit. Initial tracer migration was along the line of the steepest hydraulic gradient with very little influence from structure particularly on the initial pathway. The model of flow that was interpreted from the tracing was that there were several flow paths. It is likely that with shallower gradients then structure would have possibly been more influential. Recent excavations in the upper levels of the mine workings have revealed the reasons why the dye from the cored hole was never recovered in the Golf adit. During the summer of 1996 additional amounts of the rhodamine WT injected into the slanted holes in the wall of the Golf adit were recovered in a spring below the adit portal suggesting a mean flow through time of months.

The dye rhodamine WT was also injected in an open stope (near the Tressa B Shaft). The dye was rapidly recovered in the discharge from the Lady Murphy adit. from which there is a discharge of about 0.001 m/sec. This dye was recovered within several hours of injection.

A model was conceived where the shortest residence time was through the mine workings, when the tracer was injected there, the next longest was through the soil and shallowest weathered bedrock along the lines of steepest hydraulic gradient. Another pathway is through bedrock fractures but is much less rapid. It is believed these three pathways were generally described with the recovery of the four dyes that were injected. Figure 4 shows the generalized inferred flow paths between where the tracers were injected and recovered.

Environmental Isotope Analyses

Based on the findings from previous investigations the decision was made to enter the mine workings in

Chrysolite Mountain and locate, sample and measure the discharge of inflows entering the workings. During the summers of 1998 and 1999 the adits for the 1400 and 700 levels were reopened and stabilized to allow safe entry. The 1400 level adit has been completely stabilized and allows access to a drift that follows the Mary vein. which trends perpendicular to the adit. The 700 level adit has not been completely stabilized and currently only the first 60 metres of the adit is accessible. During the summer of 2000 the rest of he adit will be stabilized. The objective of this recent work was to determine the chemistry and relative age of the ground water flowing into the mine workings and to determine the relative contribution to flow and chemistry at the 1400 portal outflow from each of the inflows. Exploration of the 1400 level adit and the drift identified at least six distinct inflows. These included three chutes from levels above the 1400 level, flow into the adit from both the north and south ends of the drift (the adit trends approximately west to east) and inflow from a fracture zone at 150 metres from the adit portal.. Based on this, 12 sampling sites were located within the adit and the drift (Hazen, 2000). From September 1998 to September 1999 these locations were sampled 9 times (not all locations were sampled on all dates). At each of these sampling sites flow was measured and samples were collected for isotopic analyses including ^{18}O and deuterium.

Results of the tributary discharge measurements and the isotopic analyses clearly showed that the contributions from tributaries to the total 1400 level portal discharge were not constant spatially or with respect to time (Figure 5). Flow at the 1400 level portal increased from 2.1 l/s at “low flow” in September 1998 to 4.2 l/s on June 10, 1999. Most of the increase in portal discharge was result of a dramatic increase in flow from one of the chutes (from 0.23 l/s to 2.3 l/s). The percent contributions of these tributary flows also varied over the sampling period.

The permil variation of ^{18}O from the SMOW standard data for the 1400 level portal discharge and five tributary flows are shown in Figure 6. Two tributary flows and the discharge from the north drift into the 1400 level adit (MVN-1) and the flow from a chute which discharges into the north drift (MVN-3), varied significantly in ^{18}O between February and October 1999. The portal discharge and the other three tributaries showed less variation in ^{18}O. The inflow at MVN-1 and MVN-3 both became lighter or more depleted in ^{18}O as the season progressed. This is an indication of the contribution of recent snow melt. The ^{18}O values for snow at Chrysolite Mountain averaged about -20. The remaining inflows apparently were not affected by recent snow melt and instead were comprised primarily of older water with an isotopic signature quite different from the 1999 snowfall.

Based on the isotopic data from the inflows, the portal discharge, snow and rain a mixing analyses was completed (Hazen, 2000). The results of this mixing analyses is shown in Figure 7. As shown on Figure 7 most of the water in the 1400 level adit discharge is “pre-event” water or water older than the 1999 snowfall or rainfall. As the season progressed percentage of the portal discharge from “event” or 1999 snow/rain infiltration increased from none to about 25 %. This is an indication that most of the water represented by the high portion of the 1999 hydrograph for the 1400 level portal was comprised of water older than the 1999 snowmelt and rainfall. It is also important to note that most of “event” water in the portal discharge came from the chute which discharges to the north drift. Interestingly the discharge from this chute, about 1 l/s during high flow, contributes more than 75% of the total zinc in the 1400 level portal discharge.

The tritium data collected to date are limited but show mostly bomb spike water. A sample of ice that was permanently frozen in the 700 level yielded 28 TU’s, the discharge at the 1400 level portal was 16.5 TU’s. Both these numbers are likely to represent bomb-spike water (Clark and Fritz, 1992, p.185). The portal discharge tritium activity being the less does not represent decayed tritium, but more likely more diluted bomb water. The tritium data further support the hypothesis that most recharge for these waters in the mine workings is generally older than “recent” (<1 year) precipitation.

Inverse Geochemical Modeling

Inverse geochemical modeling can be an effective tool for helping to understand geochemical reactions that occur along a ground-water flow path. Inverse modeling combines mineral mass balance calculations with equilibrium saturation indices to simulate feasible mineralogic reactions for given Eh-pH conditions (Plummer, 1984). Combined with other lines of evidence inverse geochemical modeling can be used to help determine if ground water flows from one monitoring location to another monitoring location. The modeling requires mineralogy data between the two points of interest and metals concentration data for the two endpoints. Lanphear (1995) used the MINTEQAK code (Klusman, 1993) to perform inverse modeling to evaluate the possible hydrologic connection between the Golf Adit and bedrock wells MM3, MM17 and MM9. All three of these wells are located between the Golf Adit portal and Chalk Creek. Extensive watr quality data from these three bedrock wells and the Golf Adit inflows and portal outflow was used, along with detailed mineralogy data for the Mt. Princeton quartz monzonite. The results of the inverse modeling indicated that there is no ground-water flow path between the Golf adit and the three bedrock wells. This finding is consistant with the ground-wwater tracing efforts which indicated that the primary ground water flow paths that deliver dissloved metals to Chalk Creek do not intersect the Golf Adit. The significant metals concentrations in wells MM3, MM17 and MM9 do not result from infiltration of Golf adit water.

RESULTS

It appears the only reliable way to characterize ground-water in these settings is to combine data from a variety of tools and methods. The flow system probably can be described to have three basic components as shown in Figure 8. The residence times of each component varies, with the snow melt providing the shortest residence time. Because they interact each flow component is mixture. However, the largest volume of water is transmitted through the mine workings and out of adits. But they are master drains and combine the chemistry and isotopic signatures of many different waters. Assuming the provenance and age of the combined waters of an entire adit discharge is a gross average of several components and has limited significance and use.

During and after the snow melt there is increased flow (overflow) in the shallow weathered bedrock, which appears as significant, in terms of flux, as the mine workings flow. The efficient way that tracers were recovered show that the permeability of portions of the bedrock are far higher than suggested by the conventional wisdom of the permeability of such fractured rocks. Ground-water velocities through the bedrock are also orders of magnitude faster than is traditionally assumed. However, it can also be said that most of the flow through the system is a piston-like flow as it is obvious that isotopic signatures of recent precipitation and a sample of non-impacted ground-water (springs) are quite different to most of the mine waters (Figure 9). Metals loading studies cannot be adequate until the flow system is somewhat understood and each flow component and its relative contribution are known. A relatively small flow component that is a small percentage of the total discharge, but that is buried deep within a mine system, may impart a significant impact to ground-water and surface water. Rather than assume the whole flow system has a problem if this component can be found and defined the remedial activities proposed might be more focused and far more cost effective.

SUMMARY AND CONCLUSIONS

1. There are at least three active ground-water flow systems. A shallow flow system that is most active during "high flow" that occurs within the upper 15 - 20 metres of the bedrock. However this pathway is only saturated during and after snow melt. A second ground water flow system is characterized by strong preferential flow through fractures, faults and other geologic structures. This is a deeper, more regional flow system and is active all year. A third flow system is the flow of ground water through the mine workings. This system is highly perturbed and is a combination of fracture flow and channel/conduit flow.

2. Stream tracing and ground-water tracing techniques are useful in helping to accurately measure steam flow identifying areas ground-water discharge to a stream, and calculating metals loading to streams.

3. Environmental isotope data have been shown to be a very useful in describing the nature of recharge and relative ages, in terms of the annual precipitation of ground waters and mine waters.

4. There is ample evidence that suggests that most water in this system is relatively old water in terms of a 1-year cycle of precipitation and melt. The tritium data suggest that a proportion of the water could be several decades old, and that this is mixed in varying proportions with younger, or possibly older water.

5. Impacted waters might only be a fraction of the total discharge and it may be false economy to obtain gross average measurements instead of more specific data. The greater cost of gaining more information may be outweighed by the savings made when sites face remedial action.

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